FINAL TECHNICAL REPORT: The Effects of Seismic Anisotropy on Regional Seismic Wave Propagation

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ABSTRACT

Crustal rocks can be highly anisotropic. due to 1) oriented minerals 2) oriented cracks, and/or 3) thin layers of material with different elastic stiffnesses. Crustal Love and Rayleigh surface waves couple strongly for anisotropic structures that do not possess a vertical axis of symmetry, and cause explosions to generate significant shear motion on the transverse component of seismograms. We developed theory and 1-D layered-media synthetic seismogram codes for anisotropy with an arbitrary axis of symmetry. One code version can synthesize surface waves with periods $100 > T > 0.4$ sec. Another code version can synthesize teleseismic body wave reverberations up to 5 Hz. We determined that a tilted axis of symmetry enhances Love-Rayleigh coupling and the scattering of P-waves (compressional) to S-waves (shear). Using P-S scattering, we found evidence for strong ($> 10\%$) anisotropy in the deepest and shallowest crustal layers beneath seismic station ARU (Arti, Russia), an "open" seismic observatory proximal to the Novaya Zemlya nuclear test site. We also developed a wavelet-based signal processing algorithm that picks out correlated "signals" from uncorrelated "noise" in an optimally bandpassed manner. Using the Terrascope regional array in California. we applied this algorithm to reconstruct, for a single correlated signal, anomalous amplitudes and polarizations at individual stations, allowing more "signal" to be recovered than via standard "stacking."

EXECUTIVE SUMMARY

Our research focussed on two areas: 1) the effect of seismic anisotropy on the scattering of surface and body waves in continental regions, and 2) developing of a wavelet-based signal processing algorithm to detect transient seismic signals. Our major results can be summarized as follows

• We developed a flat-layered surface wave synthetic seismogram code to study the effect of crust and upper-mantle anisotropy on synthetic seismograms. Overtone surface waves in the 0.1-5 Hz range tend to be trapped in the crust. Crustal Love and Rayleigh waves have similar dispersion, and so couple strongly with just 1-D anisotropy. This contrasts with fundamental-mode surface waves that penetrate significantly into the mantle – these need lateral anisotropic structure to interact strongly.

• By modelling long-period seismograms in the Tibet region using data from a portable broadband-seismometer deployment, we demonstrated how Love-Rayleigh scattering occurs across a geological transition, in this case the Tangula Shan mountain range between Lhasa and the northern Tibetan Plateau. The source of this scattering appeared to be at 100–300-km depth in the mantle and not in the crust, because the scattering became more complex for 50-sec surface waves.

• We adapted this synthetic code to compute the effect of crustal anisotropy on the generation of teleseismic body-wave coda. Either P-, SV-, or SH-polarized waves can be accepted by the code, so that P-coda, S-coda or shear-wave splitting in multilayered anisotropic 1-D structures can be modelled. By computing "receiver functions" for both radial (P and SV) and transverse (SH) horizontal components at Global Seismic Network station ARU (Arti, Russia), we found a pattern of P-SV and P-SH scattering best explained by strongly anisotropic layers in the deepest 10km of the crust, and in the upper 5 km of the crust. Our surface wave code suggests that a crust of this type would generate 0.5-2.5 Hz crustal reverberations with equal amplitude on the radial and transverse components.

• We developed and applied a "multi-wavelet" signal processing method to detect and reconstruct transiently coherent seismic energy at a single 3-component seismic observatory and across a broadband regional seismic array. Based on the singular-value decomposition, the wavelet-based signal detector does not require a prescribed pulse shape or polarization, responding to either rectilinear, elliptical or composite particle motion. When applied to multiple stations, the multi-wavelet algorithm estimates amplitude, phase-shift and polarization anomalies at individual stations, so that waveform distortion effects across an array of stations can be estimated.

The results of this project can be obtained in the form of journal articles and, on some topics, the Yale doctoral dissertation of Liqiang Su. The relevant papers are

Levin, V., and J. Park, 1997a. Crustal anisotropy in the Ural Mtns foredeep from teleseismic receiver functions, *Geophysical Research Letters*, v24, p1283–1286.

Levin, V., and J. Park, 1997b. *P-SH* conversions in a flat-layered medium with anisotropy of arbitrary orientation, *Geophys. J. Int.*, in press.

Levin, V., and J. Park, 1997c. A *P-SH* conversion cookbook. *Pure & Appl. Geophysics*, in press.

Lilly, J., and J. Park, 1995. Multiwavelet spectral and polarization analysis of seismic records, *Geophysical Journal International*, v122, p1001–1021.

Park, J., 1996. Surface waves in layered anisotropic structures. *Geophys. J. Int.*, v126, p173–183.

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Su, L., and J. Park, 1997. Asymptotic path-integral synthetics using the strong Born approximation, submitted to *Geophysical Journal International.*

Su, L., and J. Park, 1997. Multiwavelet spectrum and polarization analysis for seismic network data, submitted to *Bulletin of the Seismological Society of America.*

Su, L., 1996. *A Method to Calculate Coupled-mode Synthetic Synthetics to Investigate Seismic Anisotropy*, Ph. D. dissertation, Department of Geology and Geophysics, Yale University.

Yu, Y., J. Park & Wu, F., 1995. Mantle anisotropy beneath the Tibetan Plateau: evidence from long-period surface waves, *Phys. Earth and Planet. Int.*, , v87, p231–246.

PRINCIPAL TECHNICAL RESULTS

Introduction

The scattering of seismic waves within the crust poses several impediments to the detection and discrimination of clandestine explosions. Scattering distorts the primary source pulse, generates coda, contributes to the effective attenuation of seismic signals, and is thought by many to generate the useful, but puzzling, L_g phase in continental regions. Scattering within the crust is conventionally attributed to "scatterers," small-scale 3-D structure in seismic velocity. Alternatively, elastic anisotropy can greatly enhance the amplitude of scattered waves, particularly the conversion of P (compressional) to SH-polarized shear waves. Generally speaking, the preponderance of P-wave radiation relative to S-wave radiation is one of the distinguishing characteristics of explosions, so such scattering impedes discrimination. In addition, scattering by anisotropy is directionally dependent. Simple models can generate 4- and 2-lobed scattered-wave radiation patterns that mimic tectonic release at an explosive source [Park, 1996; Levin and Park, 1996b].

Geologic outcrops typically display a heterogeneous mix of rock types, with markedly different seismic properties [Goff et al. 1994]. Detailed stochastic models of these rock mixtures can be used to generate scattered waves using finite difference and/or phase-screen techniques [Levander and Hollinger, 1992; Wu, 1994; Fisk and McCartor, 1993]. Given the computational complexity of the stochastic-scatterer approach, it is somewhat surprising to note that 1-D crustal models with a few anisotropic layers can generate comparable waveform distortion. Although small-scale velocity structure surely exists throughout the crust, phenomena such as cracks, rock fabrics, and outcrop-scale fold-and-thrust structures may be approximated to first order by an effective bulk anisotropy, as long as they have scale lengths less than the seismic wavelength (4–6 km for a 1-Hz P wave, 400-600 m for a 10 Hz P wave).

Surface Waves

Surface waves confined to the Earth's crustal waveguide typically exhibit strong scattering effects, most notably where explosive sources generate large amplitudes on the transverse component. Since such scattering does not occur for surface waves in a laterally homogeneous isotropic earth model, efforts at modeling have examined the effects of 3-D structure and anisotropy. Large-amplitude

small-scale structure seems required if attention is restricted to 3-D isotropic models, and methods based on phase-screens (Wu, 1994; Fisk & McCartor, 1993) and finite difference (Levander & Hollinger, 1992) have been applied, typically using a stochastically-generated velocity model. The justification for this approach is the large amount of small-scale variation in rock composition and properties evident in outcrop (Goff et al 1994). However, elastic anisotropy can also generate significant scattering. Large amounts of elastic anisotropy ($> 20\%$) are evident in many crustal minerals e.g. hornblendes and micas (Babuska & Cara, 1991), to which must be added the velocity anisotropy associated with aligned cracks within rocks (Crampin, 1984), and the directional effects of small-scale compositional layering on wave speed (Backus, 1962; Helbig, 1994).

We have developed and implemented a reflectivity-based algorithm to calculate surface wave motion in a layered anisotropic structure, in which the anisotropy can be expressed as a deviation from isotropy with a particular axis of symmetry, or a linear combination of such deviations. In some cases where both upgoing (and/or both downgoing) quasi-shear plane wave are evanescent within a layer, their particle motion vectors can become nearly parallel, leading to numerical instability (Park, 1996). This can sabotage automatic rootfinding algorithms for the surface-wave dispersion curves. We developed an alternate solution for propagating waves within the layer, which removes this instability in these exceptional cases.

Because the dispersion characteristics of higher-mode Love and Rayleigh surface wave are quite similar, they can suffer strong coupling in a 1-D layered anisotropic structure. With plausible levels of crustal anisotropy (3-10%), Rayleigh-dominant surface wave overtones can exhibit SH-amplitudes (at 2-5-sec period) that are 15-25% of total displacement. The SH-waveforms are typically not coherent with P-SV motion, and so appear as a scattered wave, not a polarization anomaly. Because these overtones, which at higher frequency combine to form the L_g phase, are composed of multiply reflected S waves trapped in the full crust, the precise location of anisotropy with depth has only a modest influence on the strength of Love-Rayleigh 'scattering.' Fundamental-mode Love and Rayleigh waves have strongly different dispersion behavior, and so are more weakly coupled.

Synthetic seismograms for crustal models demonstrate that significant Love-to-Rayleigh and Rayleigh-to-Love "scattering" can occur in the absence of lateral variation in seismic properties. This scattering depends on the azimuth relative to the axis of symmetry $\hat{\mathbf{w}}$, suffering polarity reversals that resemble the effect of a spurious addition to the source mechanism. Surface waves from explosive sources in an anisotropic crust will appear to have a component of 'tectonic release,' with fault and auxilary planes parallel and perpendicular to the anisotropic axis of symmetry.

Clear examples of fundamental-mode Love-to-Rayleigh scattering were recorded across the Tibetan plateau in a broadband PASSCAL experiment (Yu, Park and Wu, 1995). Since the dispersion of Love and Rayleigh fundamental surface waves differ greatly, this suggests that strong lateral gradients in azimuthal anisotropy exist beneath the plateau. More intense surface wave scattering is observed at intermediate periods ($T \sim 50$s), which suggests that the cause of the long-period quasi-Love waves lies in the upper mantle, not the thickened crust of the plateau. A detailed analysis of the data indicates that the long-period waveform anomalies are generated beneath the central Tibetan Plateau, where the structural trend implies deep deformations induced by continental collision. The absence of quasi-Love anomalies at the westernmost station of the PASSCAL

array suggests the east-west extent of this mantle deformation is limited. Some, but not all, of the quasi-Love observations are consistent with SKS splitting observations. We also developed a great-circle technique to calculate synthetics quickly in a 3-D anisotropic structure and also to establish an inverse algorithm because of the linear property of differential seismograms (Su and Park, 1997a; Su, 1996). These synthetics compare well with Born synthetics for 3-D anisotropic structures, which implies that, for the models we have considered, Love-Rayleigh scattering occurs primarily along the great-circle path, rather than via side-scattering. We use the great-circle technique to fit waveforms recorded in Tibet. We confirmed that the observed waveform anomalies in the southern part of the Plateau can be well explained with a strong anisotropic gradient zone beneath the central Plateau. An additional anisotropic zone in central Alaska can be used to fit details in the Tibet data better.

Body-Wave Reverberations

The occurrence of P-to-SH conversion is common in teleseismic P waves, and has been observed in a variety of tectonic environments. Two explanations, besides misaligned seismometers, are typically offered: a) ray divergence from the great circle path due to velocity heterogeneities (e.g., *Visser & Paullsen* 1993, *Hu* 1993) and b) the presence of inclined interfaces beneath the receiver (e.g., *Owens & Crosson* 1988, *Zhu et al.* 1995). Our modeling suggests an alternative explanation in terms of flat-layered anisotropy. If all velocity discontinuities in a medium are horizontal, their cumulative effect on an upgoing seismic wave may be represented by a "transmission response," readily calculated for any number of interfaces using reflectivity techniques. We use this approach to compute 3-component synthetic seismograms in a 1-D anisotropic layered medium. A compressional wave in an anisotropic velocity structure suffers conversion to both SV- and SH-polarized shear waves, unless the axis of symmetry is everywhere vertical or the wave travels parallel to all symmetry axes.

With this in mind, we compiled P-coda data sets from selected Eurasian stations of the Global Seismographic Network (GSN) that cover broad ranges of back-azimuth. The polarity of a P-to-SH converted phase should exhibit a combination of $\sin(\phi - \phi_o)$ and $\sin 2(\phi - \phi_o)$ dependence, where ϕ is back azimuth, and ϕ_o is the azimuth of the anisotropic symmetry axis (or else the strike of a dipping interface) – see Levin and Park (1997c). Source complexities can make direct comparison of seismic waveforms difficult. To compensate, we deconvolved the source using the time-domain receiver-function technique used by Sheehan et al (1995), which can combine data from multiple events in narrow ranges of back-azimuth. A tilted axis of symmetry and a dipping interface in isotropic media produce similar amplitudes of both direct (P) and converted (Ps) phases. The relative timing of the P and Ps phases is the main discriminant between anisotropy and a tilted interface. For equivalent transverse-component amplitudes, the tilted interface has larger azimuthal variation (typically 0.5-1.0 second) in the $P - Ps$ differential arrival time. Seismic anisotropy with a tilted symmetry axis leads to complex synthetic seismograms in velocity models composed of just a few flat homogeneous layers. It is possible therefore to model observations of P codas with prominent transverse components with relatively simple 1-D velocity structures.

We attempted more than one method for inferring crustal anisotropy from $P - S$ converted energy in the P-coda. At station ARU (Arti, Russia), we formed "receiver functions" for data in

narrow azimuth ranges, in order to highlight the angular variation in converted-wave amplitude, diagnostic of anisotropy (Levin and Park, 1997a). In this approach, we used trial-and-error forward modelling to find a crustal model consistent with major data features. We obtained a 5-layer velocity profile with substantial (15%) seismic anisotropy in both the lowermost crust and a low-velocity surface layer. Assuming hexagonal symmetry, the lowermost crust has a tilted "slow" symmetry axis i.e. an oblate phase velocity surface. The strike of the axis is oblique to the north-south Urals trend, but deviates $< 20°$ from the mantle fast-axis inferred from SKS splitting. The magnitude and tilt of the model's anisotropy suggests that fine layering and/or aligned cracks augment mineral-orientation anisotropy near the top and bottom of the crust. Quick et al. (1995) argue that deep-crustal exposures near Ivrea, Italy, record an imbrication of peridotite and metapelite lenses in a crust-mantle transition layer of substantial thickness, later intruded by mafic igneous rocks. This type of km-scale petrofabric, mixing high-velocity mantle rocks with strongly-anisotropic metamorphosed sediments (see Burlini & Fountain (1993)), is broadly consistent with the basal crustal layer we infer beneath ARU.

In another approach, we used a genetic algorithm search technique on one to six P coda at a time, to estimate the potential for nonuniqueness in the interpretation of sparse data (Levin and Park, 1977b). Synthetic inversion tests argue that anisotropy near large velocity jumps can be detected with some confidence, but that a single P coda can be fit adequately by models with quite different isotropic velocity profiles. Joint analysis of observations from different azimuths is necessary to constrain the anisotropic symmetry-axis adequately. In both data and synthetic-seismogram experiments, however, the use of sparse data often often constrained only a "slow" and a "fast" direction in an anisotropic layer, leaving the third direction poorly resolved. Use of P-coda data densely-sampled in azimuth, at least at ARU, appears capable of removing this ambiguity, but it deserves further attention.

At other stations in eastern Russia (YSS, YAK, PET), pulses in the transverse-component receiver function show polarity reversals with back-azimuth, suggesting that they are generated by either anisotropy or significantly tilted crustal interfaces. Although modelling of this data was not performed, we note that a similar azimuthal sweep in P-codas from Tibet was interpreted by Zhu et al (1995) to require an interface tilt of 25° and a 20% velocity inversion. (Only amplitudes were modelled, not $P - Ps$ differential travel times.) In such a context, anisotropies of 5-15% in the upper crust may seem less implausible.

Multi-wavelet Polarization Estimation:

We developed an algorithm, based on the wavelet transform and multiple taper spectral analysis, for providing a low-variance spectrum estimate of a nonstationary data process (Lilly and Park, 1995). The "multiwavelet" algorithm uses within each frequency band a number of mutually-orthogonal Slepian wavelets optimally concentrated in frequency. A sum of squared wavelet transforms with the Slepian wavelets results in a single spectrum estimate which is both low-variance and resistant to broadband bias. The multiwavelet algorithm is used to estimate the time-varying spectral density matrix $\mathsf{S}(f,t)$ for two or more time series, in particular three-component seismic data. Coherent 3-component motion is described by motion along a single trajectory with appropriate projections onto the three component axes. This trajectory is found through applying a singular

value decomposition (SVD) to a matrix $M(f,t)$ of wavelet transform values. The normalized first singular value of the SVD determines whether a correlation among the three components of the seismogram is statistically significant. Where significant, coherent particle motion is reconstructed by a linear combination of the wavelets with coefficients specified by the first left singular vector. The polarization of this motion with respect to the coordinate axes is given by the first right singular vector. Where the wavelets are real-valued, the usefulness of this method is limited to cases in which the three components of the seismic record oscillate in phase with each other, as is often the case for seismic body waves. Elliptical polarization is handled by pairing even and odd Slepian wavelets into complex-valued wavelets, capable of detecting phase shifts between components. Lilly and Park (1995) demonstrate the multiwavelet spectrum and polarization estimators on seismic data from a large shallow earthquake in the Solomon Islands, and from the recent deep earthquakes beneath Fiji (9 March 1994) and Bolivia (9 June 1994).

We extended these ideas to a multiple-station seismic analysis method, applied to 20–200 sec surface wave data from the Terrascope regional network in Southern California (Su and Park, 1997b; Su, 1996). Unlike conventional stacking techniques, this method uses a singular-value-decomposition (SVD) to allow for differing polarization behavior among stations, and can be used to detect amplitude and polarization anomalies *within* a seismic array or regional network. Multi-wavelet polarization analysis detects weak amplitude anomalies, but strong polarization anomalies, within the aperture of Terrascope. The singular values of the SVD show that array-correlated Rayleigh and Love waves are retrieved well. For events in the western and southwest Pacific, surface wave observations at inland stations suffer significant 'refraction' relative to the great-circle path, while the coastal stations suffer little polarization anomaly.

In order to interpret the array-polarization estimates of surface waves, we computed synthetic seismograms using coupled free oscillations for idealized isotropic and anisotropic models of the uppermost mantle beneath Southern California. The fast mantle root of the Transverse Ranges has been inferred from body-wave traveltime inversion (Humphreys and Clayton, 1990; Revenaugh, 1995) to express regional compression related to the "big bend" of the San Andreas Fault in southern California. Its high-velocity mantle root has been modelled by Humphreys and Hager (1990) as a small-scale convection feature in the upper mantle. In the same region, Liu et al (1995) reported strong SKS splitting with an east-west fast axis. For an anisotropic model, we prescribed 6% P-wave and 4% S-wave anisotropy in the block with an east-west fast axis, an orientation consistent with both shear-wave splitting and regional compression. Although we set an unreasonably high S-wave velocity perturbation of 20% for the isotropic model, it fails to explain the observed polarization anomalies, especially when compared with the more modest perturbations of the anisotropic model. The waveform comparison suggests that anisotropy is an important influence on the surface wave propagation direction, and that Terrascope particle-motion deflections confirm the existence of upper-mantle anisotropy beneath southern California.

SUMMARY AND RECOMMENDATIONS

Summary: Synthetic seismograms for anisotropic crustal models demonstrate that significant Love-to-Rayleigh and Rayleigh-to-Love "scattering" can occur in the absence of lateral variation in

seismic properties. This scattering depends on the angle between wave-propagation and the axis of symmetry $\hat{\mathbf{w}}$, and can cause Love-Rayleigh scattering to resemble a spurious addition to the source mechanism. This effect could masquerade as 'tectonic release' in some settings.

Synthetic seismograms show that a simple volume of modestly anisotropic rock can cause significant surface wave refraction and polarization anomalies in the 20-100 sec range, more efficiently than an isotropic velocity gradient. Array-polarization analysis of Terrascope data suggests a significant anisotropy in the mantle beneath southern California, consistent with the direction inferred from shear-wave splitting in and around the Transverse Ranges. This result suggests that crustal anisotropy may cause significant arrival-azimuth deviations in surface waves at higher-frequency.

Codas of steeply incident P waves with prominent transverse components can, in some cases, be modelled with relatively simple 1-D velocity structures. The $P - SH$ conversion occurs at interfaces where one or both layers are anisotropic. A tilted axis of symmetry and a dipping interface in isotropic media produce similar amplitudes of both direct (P) and converted (Ps) phases, leaving the relative timing of the P and Ps phases as the main discriminant. Polarity reversals with back-azimuth are evident in the transverse-component "transmission response" of several Eurasian GSN stations, strongly favoring either anisotropy or tilted ($> 15°$) interfaces in the crust.

Recommendations: Rayleigh-Love 'scattering,' significant in a 1-D anisotropic crust, will be larger if the anisotropy varies laterally, e.g. across a mountain range and/or crustal suture. Preliminary results confirm the empirical "speed bump" model of Love-Rayleigh coupling, in which the largest polarization disturbances occur when the axis of symmetry is angled $\pm 45°$ to the source-receiver path. The full 1-D layered anisotropy code can be used to ground-truth perturbative approaches to generating synthetic seismograms.

The polarization deflections in Terrascope data that we attribute to regional anisotropy may be important in actively deforming regions in Eurasia and other regions of nonproliferation concern. Therefore, network data from Kirghizstan, the CDSN, and PASSCAL data from Baikal region should be examined for these effects. Examining data from a smaller-aperture array, to examine polarization effects at higher frequency, would also be desirable.

We have demonstrated the potential impact of P-to-SH conversion by 1-D anisotropy in the crust, but further work must be done to put this knowledge can be of practical use. Deconvolving crustal reverberations with a receiver-function code seems a promising way to equalize source effects in this effort. We expect some ambiguity between anisotropy and tilted interfaces, but constraints from local geology and tectonics should resolve many cases. Combining information from P-coda and network-polarization may reveal a common source for waveform distortion and deflection in data from earthquakes and explosions.

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APPENDIX: COMPUTER CODES DEVELOPED UNDER THIS CONTRACT

Several FORTRAN computer codes were developed in the course of this contract, and have been already shared with other researchers. In particular, codes for synthetic seismomgrams in 1-D anisotropic structures are available for both surface waves and teleseismic body waves (in the form of upgoing waves at the base of a layered structure). The multi-wavelet algorithm in Lilly and Park (1995) was originally written in MATLAB commands, a popular computing package. A FORTRAN code that computes Slepian wavelets is also available. These codes can be found on the anonymous ftp server at love.geology.yale.edu. To retrieve them, type

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ftp love.geology.yale.edu
login as anonymous
cd pub/park/AFOSR
ls
prompt
mget *.*
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